Architectural Engineering: Engineering approaches for the Design for Manufacturing and Assembly for the Housing sector

Ornella Iuorio[1][0000-0003-0464-296X]

[1] Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Milan 20133, Italy

Abstract. Prefabrication is spreading in the Global North due to the necessity to build, in a short time, a large volume of new housing for an exponentially growing global population, while at the same time achieving high standards in terms of aesthetic, structural safety, and energy performance. Design for manufacturing and assembly is at the base of prefabrication. Among the variety of available prefab technologies, those based on lightweight steel profiles are particularly well suited for low and mid-rise housing. Although this technology is spreading, for it to be applied at a large-scale, it still requires to be optimized to reduce the amount of material and fabrication waste, lower fabrication time, and reduce costs. The optimization requires understanding and improvement of the mechanical behavior. It is worth considering that the structure's cost can reach up to 20% of the total expenditure and its associated embodied carbon can make up as much as 40% of the overall construction's embodied carbon. Therefore, favouring a composite system that can also facilitate achieving good energy performances with lower embodied carbon is paramount. In this framework, this paper presents the results of an interdisciplinary international research project aiming to optimize a housing system's mechanical and environmental performance for mass production. It presents the experimental objectives and results and the impacts that design decisions have made on the environmental footprint of the developed system. The presented interdisciplinary experimental approach, which is characteristic of architectural engineering, could be used in the future for the development of further innovative systems.

Keywords: Prefabrication, embodied carbon, construction industry, optimization, steel and composite systems.

1 Introduction: Architectural Engineering in UK

Architectural Engineering study programs are deeply rooted in Northern Europe and the United Kingdom, with graduates with a multidisciplinary profile who find employment within a few months of graduating in international design groups, thanks to their marked versatility. The courses in Architectural Engineering are characterized by having 50% of the activities developed through multidisciplinary laboratories whose objective is the development of increasingly complex buildings, developing the architectural project in each laboratory, starting from the first to the last year, structural and physical aspects of the building, up to highly energy-efficient solutions. It is through this triple teaching and research experience that highly interdisciplinary figures are formed, who, for example in the United Kingdom, can enroll in the register of architects (ARB), engineers (ICE, IStructe) and service engineers (CIBSE). Architectural Engineering is, therefore, a key, interdisciplinary discipline, that combines architectural qualities with performance evaluations of structural and environmental engineering, and which finds its full expression in interdisciplinary design.

In support of this thesis, this article presents an international research experience, in which interdisciplinary knowledge of architectural engineering rooted in a strong structural knowledge was the basis for the development of a modular prefabricated system based on dry technologies in cold-formed steel (CFS), for the production of single and two-family homes on a large scale.

CFS construction systems are finding wide application in industrialized countries [1]. Nonetheless, European technical codes have not yet advanced to the point of allowing the design of systems in which steel collaborates with the cladding panels also from a mechanical point of view. To develop such "composite" systems is therefore necessary to resort to experimental characterization tests. This is what happened within the knowledge transfer partnership between the University of Leeds and industry, as part of the financed project titled “Optimization of lightweight steel systems for large scale manufacturing of modular homes”, led by the Author, having as its objective to develop a construction system optimized for the large-scale production of two-storey single- and semi-detached houses, based on the use of thin steel profile construction systems, that are dry-assembled by mechanical fasteners, which are defined for fast manufacturing and to significantly improve the structural performance, safety, and sustainability of modular homes.

To achieve this, the work aimed to shift the structural design of these CFS modular homes from the steel-bracing design to the sheathing-braced design, to reduce the amount of material, facilitating the manufacturing process, and reducing the embodied carbon. The work involved both experimental and numerical studies.

In this paper, section 2 reports the research methodology adopted for the design, testing, and evaluation of environmental impacts. Section 3 discusses the results of both the experimental tests for the definition of the mechanical behavior of the newly developed system, and the results from the life cycle analysis, and compares them with those evaluated for the previous solution, defined in this paper as

“Standard”. Section 4 reports the main conclusions, highlighting the impacts of the research and reflecting on the multidisciplinary methodology.

2 Multidisciplinary methodology to develop design for manufacturing and assembly of housing systems

The methodological approach adopted in this work encompasses systemic design, experimental tests, and life cycle analysis. Specifically experimental analysis was primarily used to mechanically characterize the main structural components of the proposed composite system, in which CFS profiles collaborate with both oriented strand board (OSB) panels and cement panels (CP) to withstand both vertical and horizontal loads. Numerical studies were also used to parametrically study the impacts of a series of wall parameters in terms of shear capacity, but these are outside the scope of this paper. Moreover, simplified numerical studies were used to study the embodied carbon of the proposed system and to compare it with previously commercialized systems, to understand the achieved improvement in terms of carbon impacts, and to foresee further future reductions.

2.1 Systemic design

The integration of Design for Manufacture and Assembly (DFMA) principles into the design of prefab systems has been shown to improve construction practices and technologies significantly [2, 3]. This is particularly evident in the optimization of materials and coordination, leading to enhanced productivity and cost-effectiveness. However, the application of DFMA in the prefabricated construction industry is still limited, indicating a need for further research and development in this area. This project aimed to optimize the structural system of a CFS modular housing system, which was starting to be commercialized in UK, while speeding up the production line in the factory and reducing waste. Taking into consideration that in CFS construction systems, the most critical elements to be designed and built are the load-bearing walls, as from them, the correct behavior of this construction typology depends, speeding up wall production was essential. Given that the time spent in connecting the CFS profiles to the sheathing panels was critical, and that walls needed to be moved safely along the production line (Fig. 1), then optimizing screws and sheathing patterns, while guaranteeing the required mechanical performance was topical.

To achieve this, it was needed to understand the impact of connection patterns on the mechanical behavior of the wall system. Previous studies have demonstrated that the shear capacity of a CFS-sheathed wall is proportional to the number of connections between CFS members and sheathing panels, and that screw spacing matters [4, 5]. However, little has been discussed about the effects of spacing variations. This research, aimed to enable the wall connections to be realized through a high-speed penalizing system, and that, required some flexibility in the definition of screw patterns. Therefore, the experimental study was also intended to understand and verify screw and sheathing patterns variations, and their results (discussed in section 2.2 and section 3) informed directly the production line organization.

Fig. 1. Production line of CFS wall system for modular applications. © 2021.

2.2 Experimental studies

Experimental studies were carried out in three phases. In the first phase, components, i.e. steel, single screws and screwed connections between CFS profiles and OSB or CP panels were tested, to verify the tensile strength of steel, and to characterize the shear capacity of screws between CFS and panels. To this end, 32 tensile steel strength tests, plus 20 lap-shear tests on screws, and twenty-seven shear strength of connections were carried out. Hence, full-scale wall tests were performed. Specifically, in the second phase, four walls with a length of 2400mm and fully sheathed on one side of the CFS frame were tested under in-plane shear loading. The third phase, instead, aimed to evaluate the effect of openings on the shear response of CFS walls, with a wall length of 4800mm. In particular, three wall typologies with opening configurations were tested, representative of a ground floor rear wall (GF-RW) with a large opening, a ground floor front wall (GF-FW) with a door and a window opening, and a typical first floor (FF) with openings. These wall typologies were selected to represent the worst-case scenarios in terms of opening ratio among those to be manufactured by the housing provider, and they had a sheathing area ratio between 0,53 and 0,77. Moreover, two tests were performed on walls having the same geometrical configurations of GF-RW and FF, but which represented the “Standard” system designed by the industry before the beginning of the research project led by the Author, and they used steel bracing to achieve the required shear capacity. These last two tests were performed to understand the changes in terms of wall shear strength and stiffness due to moving from a steel bracing to a sheathing braced approach. Figures 2 and 3 show the experimental campaign tests.

Every wall was composed of studs, tracks, and blocking profiles made of C profiles (C100-41-1.6) with a steel thickness of 1.6mm and steel nominal grade 450MPa. Studs were spaced at 600mm. Three lines of blockings were placed, at 610 mm from the bottom, at mid-height of the wall, and 213mm from the top of the wall. Locating blocking towards the bottom of the wall was needed to place cement panels (CP) on the bottom part of the wall to avoid humidity growth. Full-height 15mm oriented strand board (OSB3) panels are placed in central part of the wall, to act as the primarily shear-resisting elements. While, OSB panel strips are placed toward the top of the wall, to be assembled at a later stage of the production line, to leave the opportunity to move the wall along the production line, and be lifted, during the module assembly. Self-tapping screws were used to connect sheathing panels to the CFS members, and their spacing varied between 75mm, as used in the central part of the GF-RW, up to 300 mm as used for OSB strips used at the top of the walls. These variations were chosen to achieve the required shear capacity, while at the same time, allowing to connect the screws in the central part of the walls through high-speed paneling systems, and instead using a lower number of screws where they needed to be connected with a common hand-screwier. Following requirements for the perforated design method, Simpson Strong-Tie HTT22E hold-downs were installed at the end bottom corners of the walls during the testing. Finally, ledger beams were located at the top and bottom of the wall, towards the inside face, to replicate the presence of the floors.

The tests were performed under displacement-controlled quasi-static loading, in agreement with BS EN 594 (1996) [6], which is currently adopted in the UK for wall tests of both wooden and CFS frames. The code prescribes both the specimen arrangement and the loading protocol. The walls were assembled in the factory and brought to the lab, to be vertically placed on a composite base rectangular hollow beam made by two U sections and welded to the string floor. On the top of the walls, a U spreader beam was placed to allow the distribution of the horizontal load across the wall. Linear Voltage Displacement Transducers (LVDTS) recorded vertical and horizontal displacements. Test results are discussed in section 3.

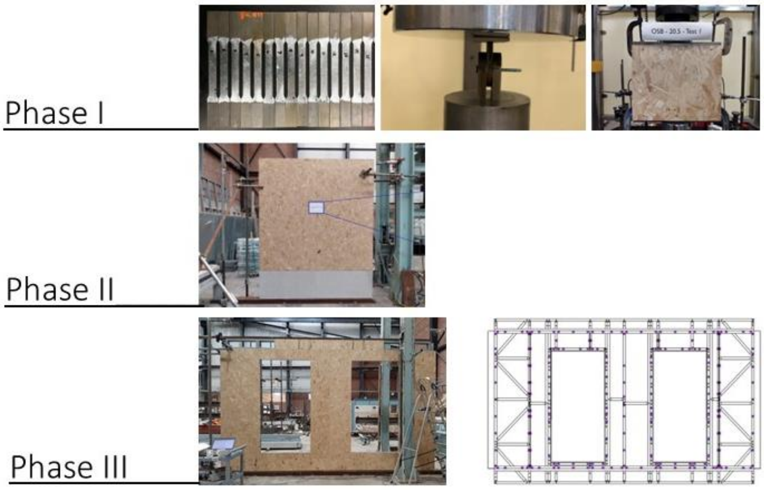

Fig. 2. Overall experimental campaign, with phase I to study tensile strength of steel members, shear capacity of screws and shear behavior of connections; Phase II to characterize the shear behavior of walls fully sheathed with OSB and CP; and Phase III to study the shear behavior of walls with openings and compare them with previously commercialized systems having steel bracings. © 2024

Fig. 3. Walls with openings: a. ground floor with 2 openings (GF-FW); b. ground floor with one large door (GF-RW); c. first floor (FF-FW) with two openings. © 2021

2.3 Life cycle analysis

Life cycle analysis (LCA) was carried out to understand the impacts of the new design in terms of CO2e. Specifically, a two-storey single-family house of 81m^2 was considered as case study in two configurations, which will be identified here as “standard design” and “new design”. The goals of the LCAs developed in this study were: 1. to investigate the environmental impacts of the newly designed CFS system in a cradle-to-grave approach, to understand what are the components that are mostly responsible for the overall embodied carbon (EC); 2. To compare the EC of the newly designed system with the previous one.

The LCA was carried out in a “cradle-to-grave” approach and includes the production stage (A1–A2–A3-A4-A5), and the end-of-life stages C and D. The B stage was not included in the study as, given the nature of this system, it was not considered feasible within the lifetime of the building to replace components, plus there is limited knowledge about maintenance and repair of this structural system.

The LCA analysis was developed in agreement with the ISO 14040/44 standard [7] and following the RICS simplified methodology [8].

For the inventory, the amount of materials was retrieved by BIM files of the investigated house. The total house mass was for the standard system equal to 24.144 tons and 25.004 tons for the newly developed system. For the LCA, the bill of material for the following construction elements was compiled: a. the foundations (composed of shallow reinforced concrete beams for the standard solutions and blocks for the new solution); b. load-bearing walls and roof (without considering insulation and finishing, as they are considered not to change between the standard and new solution); c. ground floor and intermediate floor; d. internal walls (note that for the non-structural internal partition walls were adopted wooden frames in the newly developed system).

The EC coefficients were retrieved when possible from the EPDs of the adopted materials, for both the A1-A3 stage, the C1-C4 stage, and D. When not directly available, the coefficients were retrieved by the European inventories. 140 km was considered as the distance from the factory to the construction site, and heavy goods vehicles were considered for transportation.

3 Results

This section discusses the main results of the experimental tests and the life cycle study.

3.1 Analysis of experimental results for wall tests

All wall test observations showed that the CFS frame tended to deform in a parallelogram and the sheathing boards aimed to rotate. This was true for both walls without and with openings.

When walls with openings are considered, then, given the presence of ledger beams at the top and the bottom of the walls and the specific sheathing arrangement, which included full-height sheathing boards in the center of the wall and short-height panels on the top and bottom part, then the central part of walls were to experience larger deformation, with specifically the central sheathing panels being subjected to larger rotation. This determined pull-through of the screws predominantly around the edge of the central panels. As deformation increased, cracks at the corners of the opening started to propagate. The wall with one large opening (GF-RW, Fig.4) walls showed significant diagonal cracks in each corner, with large propagation in both the OSB panels and the bottom CP panels. In the walls with two openings (i.e. GF-FW and FF-FW) the first cracks appeared in the top right top corner and left bottom corner of the opening placed at a larger distance from the applied horizontal load and followed by cracks at the other opening corners. In these walls, bottom sheathing boards did not show any significant deformation.

Fig. 4. Failure mode of one of wall with opening (GF-RW), showing the overall deformation and the diagonal cracks at top right corner and the bottom left corner. © 2021

Shear strength (Fmax) and stiffness were calculated according to BS EN 594 (2011) and are summarized in Table 1 for both Phase II tests on walls fully sheathed (labeled as GF, and FF) and Phase III tests on walls with openings (labeled as GF-FW, GF-RW, and FF-FW) and the two walls with opening and steel bracing (labeled as GF-K, and FF-K).

The results show that:

- In the phase II tests, the shear capacity comparison between the two investigated wall typologies (ground floor GF, which include both OSB and CP panels, and First floor walls FF, which includes only OSB panels) shows that GF typology, which included CP panel strips at the bottom of the walls, had a much lower racking capacity. Indeed, walls fully sheathed with OSB3 panels have a shear capacity that is at least 1.5 times higher

- In phase III tests when openings are considered, the results showed that the opening mostly influences the stiffness of the walls. Indeed, when comparing the FF-FW with opening, with a similar without opening (from phase II), the stiffness decreased by about 6.4%. It is also evident that reducing the screw spacing has a larger contribution to the shear strength of the walls.
- GF-FW and FF-FW exhibit similar shear strength (about 59.5kN) but GF-FW is stiffer. GF-RW with one large opening, but a 75mm screw spacing in the central part of the wall, has a higher shear strength (62.4kN), but low stiffness (1.82 kN/mm) due to the large opening.
- When comparing walls with openings braced only by sheathing panels, with those with steel bracings, it is shown that steel bracing slightly increases the shear strength. In terms of stiffness, GF-FW shows a higher stiffness than GF-K. However, these wall systems are never used to the maximum of their shear capacity, if used for low-rise buildings up to two floors. The walls without steel bracing are, hence, shown to fully respond to the required capacity, also in the case of large openings. Given that the walls without bracing allow material waste reduction, embodied carbon reduction and speed of construction, as discussed in the following sections, they have been preferred.

Table 1. Wall tests results

	Wall	Test	Shear Strength	Stiffness
			[kN]	[kN/mm]
Phase II	GF	2	44.12	2.48
		3	39.46	2.17
		Mean	41.79	2.32
	FF	2	60.92	1.95
		3	64.04	2.13
		Mean	62.48	2.04
Phase III	GF-FW	1	55.62	2.02
		2	61.4	2.49
		3	61.61	2.54
		Mean	59.4	2.35
	GF-RW	1	64.3	1.79
		2	64.9	1.71
		3	58	1.95
		Mean	62.40	1.82
	FF-FW	1	58.68	1.7
		2	59.7	1.87
		3	60.14	1.94
		Mean	59.51	1.84
	GF-K	1	64.41	1.36
	FF-K	1	66.58	1.91

3.2 LCA results discussion

The LCA studies developed according to the procedure discussed in section 2.3, demonstrated that overall the new system had an EC of $254kgCO_{2e}/m^2$, while the standard system had an EC of $290kgCO_{2e}/m^2$. Hence the new system allowed for a reduction of CO_{2e} of about 12.5%. Figure 5 shows the results in terms of tons of CO_{2e} for the newly developed system and the standard system across the different life stages, demonstrating that the main gains in terms of reduction of CO_{2e} were in the initial stages A1-A3, which corresponds to the raw material supply, transportation from origin to industry and manufacturing. This important reduction is mainly due to the fact, that moving from a steel bracing design to a sheathing braced design, which was optimized as discussed in the previous sections, allowed for a reduction of steel used by about 12%. Given the fact that, as already demonstrated in [9, 10], the steel components are primarily responsible for the carbon footprint of lightweight steel structural systems, their use and adoption need to be optimized as much as possible. This was one of the primary goals of the overall research project since its inception, as it was the most appropriate way to apply design methodologies developed for seismic applications [4, 5] to environmentally and structurally optimized systems for large-scale manufacturing. Figure 5 also shows the benefits of the potential recycling of steel components in the D module. The calculated figure in particular considers that 85% of steel will be recycled at the end of its life, in accordance with UK practice. Finally, the right graph in Fig.5 shows that when looking at the building sub-system, the main gains in the newly developed system were in the external and internal walls.

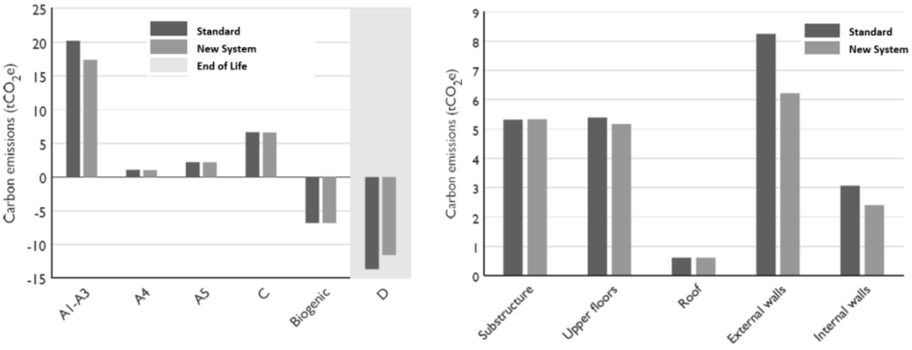

Fig. 5. Life cycle impacts of the newly developed system and the standard system: the left graph, shows the tons of CO2e of the two systems across the different life-cycle stages; the right graph shows instead the tons of CO2e for the module A1-A5, for the different subsystem of the case study © 2022

4 Conclusions

Developing a construction system for manufacturing and assembly, that aims to guarantee high structural performance, and high energy efficiency, while providing the well-being of the occupants, keeping down the costs, and speeding up production, requires, necessarily, an integrated multidisciplinary design and manufacturing approach. This approach is the basis of architectural engineering work, as taught in European universities. This paper provided an example of this approach, which has been used to develop a modular housing system in UK, to be mass-produced. The investigated system is a modular CFS housing system, which in its standard configuration was braced with steel components, and that has been optimized by adopting, instead, a sheathing-braced approach, which relies on the mechanical collaboration of CFS profiles and sheathing panels. This paper discusses the systemic design, the experimental studies, which have been at the basis of the optimization, as it was required to fully characterize the mechanical behaviour, and the life cycle studies to quantify the embodied carbon gains. The impacts of the study were environmental, industrial and societal. From an environmental viewpoint, as demonstrated the optimized system allowed to reduce the embodied carbon footprint by 12.5%, which primarily due to the reduction of steel used in the newly designed and manufactured system, and to partially to the reduction of waste, obtained by carefully designing the geometry of the sheathing panels, and thanks to the optimization of the production line. The optimization of the production line, which also included high-speed paneling, increased the speed of manufacturing, moving from making one module per week to manufacturing six modules per week, with significant gains in industrial productivity, and consequently in keeping low the costs, bringing societal benefits. Finally, the full characterization of the mechanical behavior of the newly developed system allowed the systems to be certified by BOPAS and consequently be suitable for mortgages. This multidisciplinary approach that combines BIM modeling for the design, with mechanical characterization, and life cycle thinking, all in a continuous feed loop can be applied for the study of future innovations.

References

1. Iuorio O (2007) Cold-formed steel housing, Pollack Periodica, 97-108.
2. Zhenmin Y, Chengshuang S, Yaowu W (2018) Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings, Automation in Construction, 88: 13-22.
3. Wasim M, Serra P V, Ngo T (2020) Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction – a review. International Journal of Construction Management: 3014-3022.
4. Fiorino L, Iuorio O, Landolfo R (2009) Sheathed cold-formed steel housing: A seismic design procedure. Thin-Walled Structures. 47(8-9), pp. 919-930.
5. Schafer BW, Ayhan D, Leng J, Liu P, Padilla-Llano D, Peterman K D, Stehman M, Buonopane S G, Eatherton M, Madsen R, Manley B, Moen C D (2016) Seismic Re-

sponse and Engineering of Cold-formed Steel Framed Buildings, Structures, 8, 197 – 212.

6. BS EN 594:1996 (1996) Timber structures. Test methods. Racking strength and stiffness of timber frame wall panels. BSI, London, UK.
7. ISO 14040 (2006) Environmental Management-Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland.
8. RICS (2017) RICS Professional Statement: Whole Life Carbon Assessment for the Built Environment, UK Royal Institute of Chartered Surveyors.
9. Iuorio O, Gigante A, De Masi RF (2023). Life Cycle Analysis of Innovative Technologies: Cold Formed Steel System and Cross Laminated Timber. Energies. 16(2)
10. Iuorio O, Fiorino L, Landolfo R (2019) The environmental impacts of an innovative modular lightweight steel system: The Elissa case. Journal of Cleaner Production. 238